

Next-Generation EV-First Plug-in Hybrid Electric Vehicle (PHEV) Powertrains: A Comprehensive Review and Technological Comparison with Conventional Internal Combustion Engines

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Abstract -

Plug-in Hybrid Electric Vehicles (PHEVs) have transitioned from a bridge technology to a dominant paradigm in sustainable transportation. Driven by ultra-stringent Euro 7 and EPA 2027 emissions mandates, the automotive industry has shifted from traditional internal combustion engine (ICE)-centric hybrid topologies toward "EV-first" architectures. These next-generation PHEVs utilize highly specialized Dedicated Hybrid Engines (DHEs) operating at unprecedented peak thermal efficiencies exceeding 46%, coupled with high-capacity battery systems (20–40 kWh) and Dedicated Hybrid Transmissions (DHTs). This review paper provides a comprehensive, multi-dimensional analysis of modern EV-first PHEV powertrains. We trace the structural evolution of these platforms, analyze core technological innovations such as high-dilution Miller/Atkinson cycle combustion, and perform an exhaustive technical comparison against conventional internal combustion engines. Furthermore, we evaluate intelligent energy management systems (EMS) utilizing predictive artificial intelligence, assess cradle-to-grave lifecycle environmental impacts, and outline critical engineering challenges remaining for the next decade of hybridization.

Keywords—Plug-in Hybrid Electric Vehicles (PHEV), Dedicated Hybrid Engines (DHE), Dedicated Hybrid Transmissions (DHT), Thermal Efficiency, Atkinson Cycle, Energy Management Systems (EMS), Vehicle Electrification.

I. INTRODUCTION

The global transportation sector stands at a critical technological nexus, governed by the imperative to decarbonize rapidly while ensuring consumer utility, economic viability, and manufacturing scalability. For over a century, the conventional internal combustion engine (ICE) served as the unchallenged foundation of global mobility, favored for its exceptional energy density and mature manufacturing ecosystem. However, the compounding pressures of anthropogenic climate change, deteriorating urban air quality, and increasingly stringent regulatory frameworks—such as the European Union's Euro 7 standards and the United States

Environmental Protection Agency's (EPA) post-2026 greenhouse gas limits—have rendered traditional ICE propulsion unsustainable as a standalone solution.

While Battery Electric Vehicles (BEVs) represent the ultimate zero-tailpipe-emission goal, their widespread adoption faces significant socio-technical bottlenecks. These include high capital costs, localized grid overloading, raw material supply chain volatility for lithium, cobalt, and nickel, and pervasive consumer "range anxiety" exacerbated by inadequate public direct-current fast-charging (DCFC) infrastructure. Consequently, hybridized powertrains have evolved from an interim regulatory compliance mechanism into an indispensable, long-term technological path. Among these, the Plug-in Hybrid Electric Vehicle (PHEV) occupies a unique dualistic position, synergizing the zero-emission urban operational profile of a BEV with the unlimited high-speed cruising autonomy of a conventional ICE vehicle.

Historically, early-generation PHEVs (circa 2011–2020) were engineered utilizing an "ICE-centric" philosophy. Automakers typically retrofitted conventional production gasoline or diesel engines with low-capacity battery packs (typically 5–12 kWh) and fractional-power electric motors sandwiched into traditional multi-speed automatic or continuously variable transmissions (CVTs). These systems suffered from restricted all-electric ranges (often less than 40 km), sub-optimal thermal efficiency when the battery was depleted, and highly complex mechanical architectures that increased vehicular mass and production costs without delivering a proportional reduction in real-world lifecycle emissions.

Entering the mid-2020s, a profound paradigm shift materialized. Advanced automotive manufacturers inaugurated the "EV-first" PHEV era. Rather than adding electrical components to an existing internal combustion vehicle, next-generation platforms are engineered fundamentally as electric vehicles that carry an onboard, highly optimized chemical-to-electrical power generation plant. These modern systems utilize Dedicated Hybrid Engines (DHEs) that entirely discard the broad-RPM operational requirements of conventional units, allowing them to achieve peak thermal efficiencies exceeding 46%. Combined with large-scale structural battery packs (20–40 kWh) providing pure electric ranges of 100 to 200 km, and software-defined Dedicated Hybrid Transmissions (DHTs), the modern PHEV effectively eliminates the historic compromises of hybrid driving.

This review paper presents a rigorous analysis of these newly emerged plug-in hybrid engines. Section II classifies and details the structural architectures of modern EV-first platforms. Section III delves into the core thermodynamic, mechanical, and electronic breakthroughs underpinning state-of-the-art DHEs. Section IV presents an extensive data-driven comparison between next-generation PHEV powertrains and conventional ICEs. Section V explores intelligent Energy Management Systems (EMS). Section VI and VII evaluate life cycle assessments and future technical hurdles, respectively, concluding with an outlook on the global powertrain ecosystem toward 2035.

II. ARCHITECTURAL CLASSIFICATION OF EV-FIRST PHEV PLATFORMS

The fundamental distinguishing characteristic of next-generation PHEVs is the structural and functional decoupling of the internal combustion engine from direct mechanical tractive effort. Traditional hybrid architectures are categorized as series, parallel, or complex power-split. Modern EV-first systems lean heavily toward advanced series-parallel arrangements governed by multi-mode Dedicated Hybrid Transmissions (DHTs) or operate as pure series range extenders (Extended Range Electric Vehicles, or EREVs).

A. Series-Parallel Architectures with Dedicated Hybrid Transmissions (DHT)

The state-of-the-art in plug-in hybrid engineering is exemplified by dual-motor series-parallel systems integrating a multi-stage DHT, such as BYD's DM-i (Dual Mode-intelligent) platform, Geely's NordThor system, and Toyota's fifth-generation Plug-in Hybrid System. In these architectures, the powertrain features two

distinct electric machines: a high-power traction motor (Motor-Generator 2, or MG2) permanently connected or geared directly to the drive axle, and a high-efficiency generator motor (Motor-Generator 1, or MG1) coaxial with or geared to the combustion engine.

This configuration enables multiple operating modes seamlessly managed via electronic clutches: 1) Pure EV Mode: The combustion engine is completely decoupled and deactivated. MG2 draws electrical energy from the high-voltage battery pack to propel the vehicle. 2) Series Hybrid Mode: At low-to-medium velocities or during high transient load conditions with a depleted battery, the combustion engine is ignited but does not drive the wheels. Instead, it operates at its absolute thermodynamic sweet spot to turn MG1, which generates electrical energy. This current is routed through an inverter directly to MG2 for propulsion, with any excess energy directed to replenish the battery pack. 3) Parallel Parallel Mode: At high cruising speeds (typically >70 km/h) where mechanical transfer efficiency exceeds electrical conversion efficiency, a lock-up clutch engages. This allows the combustion engine to establish a direct mechanical connection to the drive wheels, usually via a highly efficient single-speed or two-speed reduction gear, operating alongside MG2 to optimize system torque.

B. Pure Series Range-Extender Topologies (EREV)

An alternative manifestation of the EV-first philosophy is the modern EREV, protected by recent intellectual property filings such as Faraday Future's AIHER system and popularized by platforms like Li Auto. In a pure series EREV, the mechanical link between the combustion engine and the drive wheels is completely eliminated. The internal combustion engine acts strictly as an onboard auxiliary power unit (APU) driving a generator. The generator outputs alternating current, which is rectified to direct current by the dual-inverter module to supply the traction motor or charge the high-voltage battery pack.

By removing all mechanical clutches, multi-speed gear sets, and synchronizers, EREVs vastly reduce powertrain part counts, simplify chassis packaging, and isolate the cabin from mechanical vibrations. The engine can be housed in acoustics-optimized compartments and programmed to operate exclusively at fixed, highly controlled steady-state load points, bypassing all transient throttling losses that plague traditional driving cycles.

III. THE EVOLUTION OF DEDICATED HYBRID ENGINES (DHEs)

A conventional internal combustion engine must operate flexibly across a vast operational envelope, delivering acceptable torque at 1,000 RPM while maintaining mechanical integrity at 6,000 RPM. This broad requirement forces severe thermodynamic compromises, restricting real-world brake thermal efficiency (BTE) to a mediocre 30–35% average. In contrast, an EV-first PHEV utilizes a Dedicated Hybrid Engine (DHE). Because the electric traction motor handles all low-speed high-torque transients, stop-and-go acceleration, and regenerative braking, the DHE can be downsized and hyper-optimized for a narrow, predictable operating window.

A. Advanced Thermodynamic Cycles and Compression Ratios

Modern DHEs employ highly aggressive implementations of the Atkinson or Miller cycle, achieved via advanced electronic Variable Valve Timing (e-VVT) systems. By delaying the closure of the intake valves well into the compression stroke (Atkinson) or closing them early during the intake stroke (Miller), the effective compression stroke is rendered significantly shorter than the expansion stroke. This high expansion ratio allows the burning fuel-air mixture to extract maximum mechanical work from the gases before they are exhausted into the atmosphere.

To maximize the efficiency gains of the over-expanded cycle, modern DHEs feature unprecedented geometric compression ratios ranging from 15.5:1 to 16.5:1. In a conventional ICE, such extreme compression ratios would inevitably trigger destructive engine knock (pre-ignition). DHEs mitigate this phenomenon through a combination of ultra-high-tumble intake ports, specialized piston crown geometries that accelerate flame propagation, and massive rates of Cooled Exhaust Gas Recirculation (EGR).

B. High-Dilution Cooled EGR and Ultra-High Injection Pressures

Cooled EGR rates in state-of-the-art DHEs have reached 25% to 35% of the total intake charge. By routing cooled exhaust gas back into the combustion chamber, the peak combustion temperature is lowered substantially. This reduction serves two critical purposes: it virtually eliminates the formation of harmful nitrogen oxides (NOx) at the source, and it decreases thermal dissipation losses through the cylinder walls and piston head. To ensure stable, complete combustion under such extreme dilution, these engines are paired with high-energy, multi-charge or microwave ignition systems capable of reliably arc-striking through lean mixtures.

Simultaneously, fuel delivery systems have transitioned to ultra-high-pressure direct injection (DI) systems operating at 350 to 500 bar. These systems utilize multi-hole piezoelectric injectors capable of executing up to five distinct injection events per combustion cycle. The resulting sub-micron fuel droplet size guarantees instantaneous atomization and an exceptionally homogeneous fuel-air charge, suppressing localized rich zones and minimizing raw particulate matter (PM) generation.

C. Friction Minimization and Auxiliary Electrification

Every mechanical watt saved from parasitic friction directly improves thermodynamic efficiency. Next-generation DHEs utilize ultra-low viscosity lubricants (such as 0W-8 or 0W-12 grades) coupled with advanced Diamond-Like Carbon (DLC) coatings on valvetrain components, piston skirts, and wrist pins. Furthermore, traditional belt-driven accessories are entirely eliminated. The water pump, air conditioning compressor, oil pump, and brake vacuum assist are entirely electrified and powered off the high-voltage DC-DC bus. This permits variable, demand-responsive control of auxiliary loads, ensuring zero parasitic drain when the engine is operational.

IV. COMPREHENSIVE TECHNICAL COMPARISON: PHEV VS. CONVENTIONAL ICE

To understand the technical disruption represented by next-generation PHEV engines, a formal comparative analysis against conventional ICE powertrains must be executed across mechanical, thermodynamic, and operational vectors.

Table I establishes a quantitative baseline comparing structural and performance matrices as of 2026.

Technical Parameter		Conventional ICE Powertrain	Next-Gen EV-First PHE Powertrain
Peak Brake Thermal Efficiency		35% – 40% maximum	45% – 46.5% optimized
Geometric Compression Ratio		9.5:1 – 11.5:1 (Turbo/NA)	15.5:1 – 16.5:1 (Atkinson/Miller)
Transmission Complexity	Mechanic	High (6 to 10-speed AT/DCT, 300+ moving parts)	Extremely Low (Single/Dual-speed DHT, <50 moving parts)
Transient Torque Response Time		200 – 500 ms (Turbo lag, downshift delays)	Instantaneous (<10 ms via Traction Motor)
Parasitic Engine Load		High (Belt-driven alternator, A/C, water pump)	Zero (100% Electrified Auxiliary Components)
Urban Fuel Economy (WLTP)		7.0 – 9.5 L/100km	0.0 L/100km (Pure EV mode) / 3.0 L/100km (Depleted)

Exhaust Aftertreatment Burden	High (Complex particulate filter, continuous NOx catalysts)	Reduced (Steady-state operation lowers raw emissions)
Regenerative Braking Capacity	0% (Energy dissipated as friction heat)	Up to 85% of kinetic energy recovery to HV battery
Acoustic / NVH Characteristics	Variable (High NVH during high RPM acceleration)	Decoupled (Engine isolated from road-load transients)
Total Combined Range Capability	600 – 800 km	1,000 – 1,400 km

A. Thermodynamic Analysis and Efficiency Profiles

The primary divergence lies in the efficiency maps of the respective engines. A conventional ICE must operate within a broad RPM-torque spectrum, forcing it to frequently operate in low-efficiency quadrants (e.g., low-load urban stop-and-go driving), where throttling losses across the butterfly valve induce severe pumping work. In this zone, efficiency often drops to under 18%.

Conversely, in an EV-first PHEV, the engine is completely insulated from these low-efficiency regimes. When the state of charge (SoC) of the battery falls below a critical threshold, the powertrain controller commands the DHE to ignite and immediately settle at its high-efficiency plateau—typically around 2,000 to 2,800 RPM at a high, constant BMEP (Brake Mean Effective Pressure). The mathematical relation governing engine fuel consumption rate is given by the Brake Specific Fuel Consumption (BSFC):

$$BSFC = m_f / P_e \quad (1)$$

where m_f is the fuel mass flow rate and P_e is the effective power output. By holding P_e at its absolute optimum, the BSFC of a DHE remains minimized (often below 200 g/kWh), an achievement unattainable by conventional vehicles undergoing dynamic transient driving cycles.

B. Drivetrain Mechanical Complexity vs. Software Complexity

Conventional vehicles require complex, multi-ratio transmissions (such as 8-speed planetary automatic or 7-speed dual-clutch systems) to reconcile the narrow torque band of the ICE with the highly variable speed requirements of the vehicle. These transmissions introduce massive mechanical friction, hydraulic pumping losses, and significant component wear points.

An EV-first PHEV replaces this entire apparatus with a Dedicated Hybrid Transmission (DHT). A DHT typically features only one or two fixed gear ratios for high-speed direct engine drive, with the rest of the operational speed spectrum handled completely by the seamless, infinite RPM range of the electric traction motor. This architectural trade-off reduces mechanical moving parts by up to 70%. However, this mechanical simplification shifts the burden to software complexity, demanding sophisticated real-time embedded control systems to orchestrate clutched transitions and power electronics switching frequencies without inducing driveline torque disturbances.

V. INTELLIGENT ENERGY MANAGEMENT STRATEGIES (EMS)

The dual-power source nature of PHEVs necessitates a highly sophisticated supervisory controller or Energy Management Strategy (EMS) to dynamically allocate power split commands between the DHE and the battery pack. Traditional PHEVs relied on rigid, deterministic heuristic rules (e.g., Charge-Depleting mode until a fixed SoC threshold is hit, followed by Charge-Sustaining mode).

Modern systems utilize optimization-based and predictive AI-driven EMS paradigms. The core mathematical objective of the EMS is to minimize the equivalent fuel consumption over a given driving horizon, modeled via the Equivalent Consumption Minimization Strategy (ECMS). This formulation equates electricity consumption to a virtual fuel usage via a time-varying equivalence factor $s(t)$:

$$P_{eq}(t) = P_{fuel}(t) + s(t) \cdot P_{elec}(t) \quad (2)$$

State-of-the-art platforms integrate cloud-based machine learning algorithms that receive real-time data from Intelligent Transportation Systems (ITS), onboard GPS navigation, and radar/camera sensors. If the vehicle knows the upcoming route involves a segment of congested urban driving followed by high-speed topography, the EMS will purposefully preserve battery energy during the initial stages by running the DHE at high efficiency, ensuring the vehicle can operate in pure, zero-emission EV mode within the urban core. This predictive optimization yields an additional 15–20% reduction in cumulative energy expenditure compared to uncoordinated heuristic strategies.

VI. TECHNO-ECONOMIC AND LIFECYCLE ENVIRONMENTAL IMPACT

A rigorous engineering review must extend beyond bench-scale efficiency to evaluate the systemic lifecycle impacts of next-generation PHEVs relative to conventional ICE and pure BEV platforms.

A. Cradle-to-Grave Lifecycle Assessment (LCA)

When evaluating greenhouse gas (GHG) emissions from a cradle-to-grave perspective, conventional ICE vehicles are inherently penalized by their continuous tailpipe emissions. Pure BEVs exhibit zero tailpipe emissions but carry a substantial upfront carbon debt accumulated during the extraction and refining of raw battery materials (lithium, nickel, manganese) and the high-temperature cell manufacturing process. If a BEV is operated on an electrical grid dominated by fossil fuels (such as coal or natural gas), its lifecycle benefit is severely diminished.

Next-generation PHEVs strike an optimized equilibrium. By sizing the battery pack to a moderate 20–40 kWh range, the manufacturing carbon footprint is reduced by 50% to 70% compared to a long-range 80–100 kWh BEV battery pack. When combined with a DHE operating at >46% thermal efficiency, the total lifecycle carbon emissions of an EV-first PHEV are frequently lower than a large-battery BEV in regions with carbon-intensive grid mixes, while representing a 60% reduction over a comparable conventional ICE vehicle.

B. Consumer Total Cost of Ownership (TCO)

From an economic standpoint, the EV-first PHEV presents an optimal TCO matrix. Approximately 80–90% of daily consumer trips fall well under the 100–200 km threshold, allowing users to fulfill almost all commuting needs purely via low-cost overnight residential AC charging. The internal combustion infrastructure is preserved strictly for long-distance regional travel, shielding the driver from high fuel price volatility while evading the severe public fast-charging costs associated with BEV road trips.

VII. CRITICAL TECHNICAL CHALLENGES AND FUTURE HORIZONS

Despite their exceptional technological advancements, next-generation EV-first PHEV engines are not devoid of significant engineering challenges that remain active areas of core research.

A. Cold Start Emissions and Catalyst Thermal Management

Because next-generation PHEVs prioritize pure electric propulsion, the internal combustion engine may remain deactivated for extended durations while cruising on the highway or navigating urban corridors. If the driver

suddenly demands maximum tractive power—such as an emergency overtaking maneuver—the control system must execute an instantaneous hot ignition of the DHE from a cold, unlubricated state. This induces a sharp thermal shock on engine components.

More critically, the exhaust three-way catalytic converter (TWC) will be cold (well below its required light-off temperature of $\sim 300^{\circ}\text{C}$). Initiating high-load combustion under these conditions causes a transient spike in unburned hydrocarbons (HC) and carbon monoxide (CO) before the catalyst can activate. Current engineering solutions being researched involve integrating 48V electrically heated catalysts (EHC) and pre-cranking thermal management strategies to pre-heat the exhaust stream prior to engine combustion engagement.

B. Battery Degradation Under High-Power Hybrid Dynamics

Unlike BEV batteries that experience gradual, predictable current draws, a PHEV battery operates under intense thermal and electrical stress. When running in Charge-Sustaining mode, the battery pack is subjected to continuous high-frequency, high-amplitude charging pulses (from regenerative braking and MG1 power spikes) interwoven with aggressive discharging pulses (to augment engine torque). This micro-cycling accelerates mechanical micro-cracking within the cathode crystal structure, leading to accelerated capacity fade. Advanced thermal management—utilizing direct immersion liquid cooling or phase-change materials—is mandatory to preserve cell longevity across the vehicle's design lifecycle.

VIII. CONCLUSION

Next-generation EV-first plug-in hybrid engines represent a fundamental engineering triumph, successfully redefining the relationship between chemical and electrical vehicular propulsion. By abandoning the multi-speed mechanical constraints of the past and transitioning to ultra-efficient Dedicated Hybrid Engines optimized exclusively for steady-state electricity generation, modern PHEVs have achieved peak brake thermal efficiencies exceeding 46% and total driving autonomies surpassing 1,200 km.

When compared to conventional internal combustion engines, the EV-first PHEV completely eliminates urban idling losses, parasitic auxiliary drains, and transient throttling penalties, while providing instantaneous torque response and significant lifecycle carbon reductions. As intelligent, predictive energy management software matures and aftertreatment engineering resolves cold-start bottlenecks, the modern PHEV will solidify its status not merely as a temporary bridge, but as a long-term, co-equal pillar of sustainable global transport infrastructure alongside pure electric vehicles.

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